Impacts of Climate Change on the Hydrology and Water Resources of the Colorado River System

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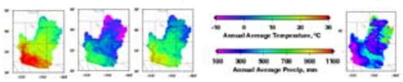
1 Colorado River

The Colorado River Basin covers 630,000 km^2 in seven states and part of Mexico. Annual precipitation ranges from over 1.1m in the mountainous headwaters to less than 0.1m in the desert areas. The annual naturalized flow at Lees Ferry, AZ, which partitions the upper and lower basins, has ranged from 5.0 to 23.7 million acre-feet (MAF), with an average of 15 MAF. The upper basin contributes roughly 90% of the annual runoff.

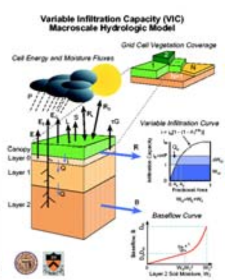
Eleven major storage projects provide approximately 61 MAF of storage (about four times the mean annual flow). These reservoirs are operated to provide flood control, hydropower generation, agricultural, industrial, and municipal water supply, fish and wildlife targets, and recreation.

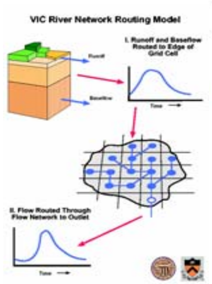


2 Hydrologic Model Implementation and Calibration

The hydrologic model used was the Variable Infiltration Capacity (VIC) macroscale land surface model (see http://www.hydro.washington.edu for model details). The model was run in a 24 hour timestep water balance mode at 1/8° spatial resolution. Forcing variables are daily precipitation, maximum and minimum temperatures and wind. Soil parameters were taken from the NRCS Soil Geographic Database (STATSGO) and land cover from the University of Maryland 1-km Global Land Cover product (derived from AVHRR). VIC water balance mode assumes that the soil surface temperature is equal to the air temperature for the current timestep. The exception to this is that the snow algorithm solves the surface energy balance at three hour timesteps to determine the fluxes needed to drive accumulation and ablation processes.

VIC Model Features:
- Multiple vegetation classes in each cell
- Sub-grid elevation band definition (for snow)
- 3 soil layers used
- Sub-grid infiltration/runoff variability



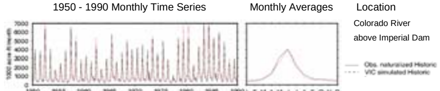


VIC Routing Features:
- All runoff exits cell in single flow direction
- Within Cell routing uses a Unit Hydrograph approach
- Channel routing uses linearized Saint-Venant equation

Validation of Runoff

The VIC model was calibrated by adjusting the soil depths, baseflow parameters, and infiltration capacity parameter to reproduce observed streamflow. Runoff from each 1/8 degree grid cell was routed to points with estimated (USBR) naturalized flows where the hydrographs were compared. Gridded VIC forcing data is available for 1950 - 2000 and naturalized flows were available for the period 1906 - 1990.

1950 - 1990 Monthly Time Series | Monthly Averages | Location: Colorado River above Imperial Dam



3 CRRM Reservoir Model Overview and Validation

A monthly time step reservoir model is used to represent the major storage facilities and their operation. Storage of the 11 major reservoirs are aggregated into four equivalent reservoirs in CRRM: Flaming Gorge, Navajo, Lake Powell, and Lake Mead. Hydropower simulations take place at these dams (except Navajo) as well as at Davis and Parker.

4 General Circulation Models and Climate Scenarios

General Circulation Models (GCMs) mathematically represent atmospheric, land surface, and atmosphere-ocean processes. The 11 GCMs used in this study represent the major global modeling centers. The specific model runs were produced for the upcoming IPCC Fourth Assessment Report (AR4). The IPCC created six plausible emission scenarios; A1F, A1B, A1T, A2, B1, and B2. With respect to global emissions of greenhouse gases (hence, in general, global average temperature increases) from warmest to coolest are scenarios A1FI, A2, A1B, B2, A1T, and B1. The A2 and B1 scenarios were chosen for this study because they are the most widely simulated over all models and because they represent the plausible range of conditions over the next century. The table below summarizes the GCMs and includes references to the details of each model.

Abbrev.	Modeling Group, Country	IPCC Model I.D.	Reference
CNRM	Centre National de Recherches Météorologiques, France	CNRM-CM3	Salas-Mélia et al.,2005
CSIRO	CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	Gordon, H.B. et al., 2002
GFDL	Geophysical Fluid Dynamics Laboratory, USA	GFDL-CM2.0	Delworth et al., 2005
GISS	Goddard Institute for Space Studies, USA	GISS-ER	Russell et al., 1995, 2000
HADCM3	Hadley Center for Climate and Prediction and Research, UK	UKMO-HadCM3	Gordon, C. et al., 2002
INMCM	Institute for Numerical Mathematics, Russia	INM-CM3.0	Diansky and Volodin, 2002
IPSL	Institut Pierre Simon Laplace, France	IPSL-CM4	IPSL, 2005
MIROC	Center for Climate Systems Research, Japan	MIROC3.2	K-1 model developers, 2004
MPI	Max Planck Institute for Meteorology, Germany	ECHAM5 / MPI-OM	Jungclaus et al., 2005
MRI	Meteorological Research Institute, Japan	MRI-CGCM2.3.2	Yukimoto et al., 2001
PCM	National Center for Atmospheric Research, USA	PCM	Washington et al., 2000

Note: GCM output was retrieved from the IPCC DDC (http://www.usgcrp.gov/usgcrp/nacc/background/scenarios/emissions.html)

5 Climate Results

Results are summarized by emission scenario and period. All results are relative to 1950-1999 (Temp changes in degrees, others as percent).

The ensemble average change (%) relative to 1950-1999 simulated historic.

Number of the 11 ensemble members that are higher (lower) than the historic simulation.

Minimum (maximum) change (%) of the ensemble members relative to historic.

SRES A2

2010-2039

	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	99.1	99.2	98.7	1.2	99.2	86.9	99.5
# higher	5	5	5	11	3	0	5
# lower	5	5	6	0	5	10	5
MIN	90.7	91.7	83.5	0.6	94.6	63.6	91.5
MAX	107.0	106.5	114.5	1.8	103.0	101.0	107.0

2040-2069

	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	98.1	98.8	94.4	2.6	97.8	78.9	95.4
# higher	4	4	5	11	4	1	3
# lower	7	6	6	0	7	10	5
MIN	79.2	82.0	60.7	1.6	87.8	48.1	76.7
MAX	113.4	112.7	118.2	3.7	104.4	106.1	106.2

2070-2099

	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	98.0	99.1	89.0	4.3	96.4	61.7	90.5
# higher	4	4	1	11	2	0	0
# lower	7	6	9	0	8	11	10
MIN	84.3	87.5	62.8	2.8	87.5	33.5	74.4
MAX	112.8	114.5	110.8	6.1	103.9	84.8	100.1

SRES B1

2010-2039

	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	101.5	101.8	99.5	1.3	99.4	84.6	97.9
# higher	7	6	4	11	2	0	3
# lower	4	3	4	0	4	10	7
MIN	91.5	93.7	77.3	0.6	93.2	58.6	84.5
MAX	111.3	110.2	116.6	1.8	104.4	100.1	104.8

2040-2069

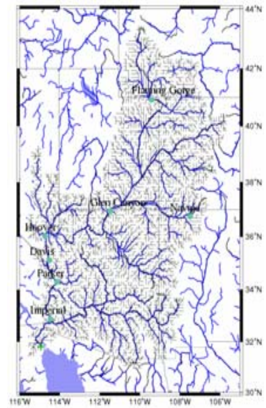
	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	99.1	100.2	92.4	2.1	98.0	74.9	93.0
# higher	4	6	2	11	2	1	2
# lower	5	5	8	0	7	10	8
MIN	89.0	91.0	72.6	1.1	91.1	52.0	81.5
MAX	109.4	109.4	111.8	3.0	103.1	99.1	102.2

2070-2099

	PRECIP	EVAP	RUNOFF	TEMP	SOIL MOIST	SWE	RO RATIO
avg	99.1	100.1	92.0	2.7	97.2	70.9	92.3
# higher	4	4	2	11	2	0	1
# lower	6	5	9	0	9	11	9
MIN	88.6	90.9	69.7	1.8	91.0	47.5	78.6
MAX	119.2	118.1	128.9	3.9	105.6	82.3	108.1

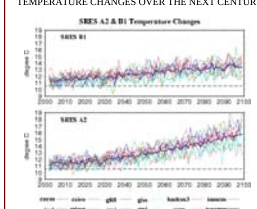
Abstract

The Colorado River system provides water supply to a large area of the interior west. It drains a mostly arid region, with naturalized flow (effects of reservoirs and diversions removed) averaging only 40 mm/yr. Total reservoir storage (mostly behind Hoover and Glen Canyon Dams) is equivalent to over four times the mean annual flow of the river. Runoff is heavily dominated by high elevation source areas in the Rocky Mountain headwaters, and the seasonal runoff pattern throughout the Colorado basin is strongly dominated by winter snow accumulation and spring melt. Because of the arid nature of the basin and the low runoff per unit area, performance of the reservoir system is potentially susceptible to changes in streamflow that would result from global warming. In this study the implications of climate change on the hydrology and water resources of the Colorado River basin are assessed through comparisons of hydrology and water resource simulations for the 100-year period 2001-2100 driven by downscaled and bias corrected output from 11 General Circulation Models (GCMs) against a 1950-1999 historical simulation. For each of the 11 GCMs, two emissions scenarios (IPCC SRES A2 and B1, corresponding to relatively unconstrained growth in emissions, and elimination of global emissions increases by 2100) are represented. Downscaled and bias-corrected transient temperature and precipitation signals were extracted from the GCMs and used to drive the Variable Infiltration Capacity (VIC) macroscale hydrologic model. Streamflow sequences from VIC were then used to drive the Colorado River Reservoir Model (CRRM) in order to project reservoir system performance under each of the climate scenarios.

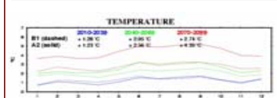


6 Climate Results cont'd

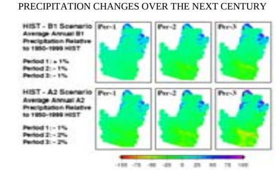
TEMPERATURE CHANGES OVER THE NEXT CENTURY



The A2 and B1 scenarios have almost identical temperature changes through the early part of the century which is reflection of their similar initial emissions scenarios. As the emissions diverge around mid century, so do the temperature increases. The higher (A2) emission scenario generates the greatest warming, with warming increasing throughout the century for both scenarios. The late summer peak in warming may be driven by a decrease in soil moisture due to a significantly earlier runoff, and therefore more energy available for sensible rather than latent heating.

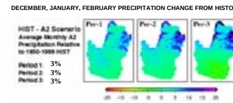


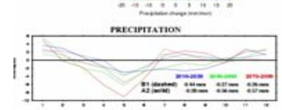
PRECIPITATION CHANGES OVER THE NEXT CENTURY



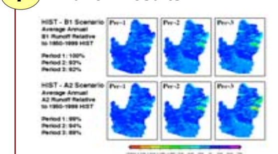
Basin average annual precipitation changes are modest for both emission scenarios. There is however a shift towards increased winter P that has implications on runoff as runoff ratios are higher in the winter. This shift helps offset some of the increased evaporation that occurs due to rising temperatures.

DECEMBER, JANUARY, FEBRUARY PRECIPITATION CHANGE FROM HISTORICAL



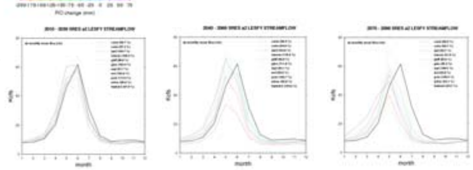


7 Runoff Results



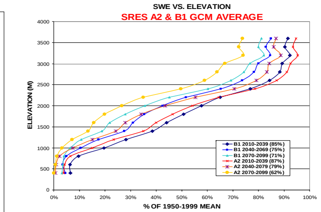
Runoff volume averaged over models is nearly unchanged in period 1 for both SRES scenarios, decreases by 7 and 6% in period 2 for the B1 and A2 scenario, respectively, and by 8 and 11% in period 3 for the B1 and A2 scenario. Although precipitation changes are modest (+1 - -2%), decreases in the runoff ratio drive reductions in runoff volume. The greatest runoff decreases are on the east side of the basin in the Rockies, whereas the lower basin has more modest changes. Higher winter and spring temperatures have a significant effect on the annual hydrograph. A higher rain to snow ratio and earlier melt advance the spring melt peak increasingly through the century.

The three plots to the right show average flows at Lees Ferry (compact point) for periods 2010-2039, 2040-2069, and 2070-2099. Dark line is the ensemble average.



8 Changes in SWE

Basin average April 1 snow water equivalent (SWE) declines by 13, 21, and 38% in scenario A2, and by 15, 25, and 29% in scenario B1 in periods 1-3, respectively. Winter precipitation volumes are greater in all future scenarios than during the historical period, leading to the conclusion that the reductions in SWE are directly attributable to higher winter time temperatures and the resulting decrease in the ratio of precipitation falling as snow vs. rain. Reductions in SWE are greatest in the low to mid elevation transitional zone.

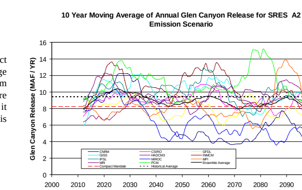


The above plot shows that the amount of snow present will decrease significantly over the next century. Snow present is a function of both snow depth (SWE in mm) and length of time it's on the ground. A similar amount of SWE that melts twice as fast would be considered 50% of the amount of snow present.

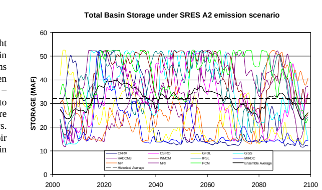
9 Preliminary Water Resources Results

The water resource results presented below are preliminary, however they do show a decrease in the basin's ability to meet the Compact mandated release of 8.23 MAF/yr (on a 10 year average) from Glen Canyon dam. Total basin storage also decreases, but only slightly. The modest storage reduction results from demand reductions during low inflow periods which trigger release reductions, and thereby artificially keep reservoir levels up. A more illustrative metric of how the reservoir system will perform in the future is delivery shortfalls. Shortfalls are triggered when Lake Mead reaches certain elevations, and are also related to the SNWA's intake elevation (1000').

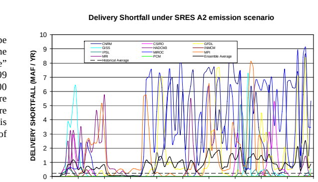
The Colorado River Compact mandates a 10 year average release of 8.23 MAF/yr from Glen Canyon Dam. Future streamflow will likely make it harder to meet or exceed this demand.



There is only a slight reduction in total basin storage which seems counterintuitive given generally reduced inflows – however it is mostly due to release reductions that are triggered by low flows. Additional reservoir sensitivity analysis is in progress.



Although there have yet to be delivery shortages in the basin, the "historical average" plotted here shows 1950-1999 streamflows with year 2000 demands. Shortfalls are considerably higher for future streamflow scenarios. This is probably the best metric of future performance.



Conclusions

For all GCMs and emissions scenarios, temperatures increase throughout the century, continuing an historic trend. Temperature changes are similar for both emissions scenarios early in the century, but begin to diverge by mid-century.

Precipitation changes vary greatly among models, but are small on an annual basis averaged over models. Most models show a shift from summer to winter precipitation, which helps mitigate runoff changes.

Averaged over models, annual runoff progressively decreases through the century, with changes approaching 10% for the A2 emissions scenario by late in the century. Snowpack progressively is reduced resulting in earlier spring runoff. However, due to the large size of the reservoirs, annual runoff changes are of greater importance.

Average reservoir levels decline slightly through the century, primarily as a result of shortfalls which trigger reductions in the water management model. Delivery shortfalls, which are a better indicator of reservoir system performance, progressively increase through the century.

References

Christensen, N.S., Wood, A.W., Voisin, N., Lettenmaier, D.P. and R.N. Palmer, 2004, Effects of climate change on the hydrology and water resources of the Colorado River Basin, *Climatic Change* 62, 337-363, January.